Ecoregional Differences in Land Cover and Water Quality in a Midwestern Watershed.

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Abstract: Omernik's ecoregions were developed to serve as a spatial framework for environmental monitoring and research. We have examined the relationship between various geophysical and land cover measures with nutrient water chemistry concentrations in 35 headwater streams (sub-watersheds) distributed across three Omernik Level IV ecoregions within the Little Miami River watershed (LMRW) in southwestern Ohio (Figure 1). For this study land cover data was extracted from available satellite imagery (National Land Cover Data Set) and the geophysical spatial measures from available digital sources (National Elevation Data Set and Ohio STATSGO soil base). We observe that the patterns and spatial distribution of geomorphologic, topographic, and land cover resources within the catchments vary across the three Omernik ecoregions, (i.e., the Darby Plain, the Loamy, High Lime Till Plain (Till Plain) and the Pre-Wisconsinan Drift Plain (Drift Plain) within the LMR watershed. In addition, while the dominant land cover element (46 – 90%) in all of these sub-watersheds is row crop agriculture, the differences in geomorphology, hydrology, and soil types within the ecoregions has lead to variations in land cover use. e.g., relative differences in percent row crop versus grass or forest within the drainage areas. We observe that the concentrations of dissolved nutrients in these headwaters streams were also distributed in a consistent and differential manner across the three ecoregions. Specifically, those sub-watersheds situated within the Darby and Till Plain ecoregions contained 27 - 42 times more dissolved nitrate nitrogen (NN), than the sub-watersheds in the Drift Plain having similar drained area, similar length of stream reach. In contrast, dissolved organic nitrogen (ON) and total dissolved phosphate (TP) concentrations were highest in the Drift Plain sub-watersheds. Approximately 90 % of the variation in the concentration of dissolved NN across all of the LMRW sub-watersheds could be explained via a step-wise multi-regression model employing a combination of land cover and hydro-geomorphic features as the independent variables. These results suggest a synergism between the geo-physical and land cover features as they impact the transfer of nutrients to streams. Likewise, these observations lend credence to the decision of various State regulatory agencies, which have used ecoregions to modulate decisions rules on water quality measures.

Introduction: The Omernik ecoregions are geographic areas of general homogeneity with respect to the ecosystems contained therein and were developed to create a spatial framework for environmental research and management (Omernik, 1995). These regions are demarcated by the abiotic (e.g., geology, hydrology, soils, and climate) and biotic (e.g., vegetation, wildlife), which they contain. It seems apparent that the particular constellation of these physiographic features and abiotic resources within an ecoregion influences the land use (e.g., agriculture) options and thereby further dictates land cover (e.g., row crop versus forest). In turn, it has been well documented that land usage and the accompanying land cover patterns in a watersheds influences the quality of the streams they surround. For example, agricultural operations have been shown to increase non-point source nutrient loadings (Jordon et al., 1997a,b). However, considerable ambiguity still exists regarding the exact relationships between the qualitative, qualitative and spatial aspects of land cover and nutrient exports to streams.

Streams receive nutrients from a variety of sources, including atmospheric deposition and land-based processes (Jordon et al, 1995), including agricultural fertilizers, and waste products, of both human and animal origin. Efforts to apportion these loadings in Midwestern streams has been stimulated by the proposed linkage between hypoxic conditions in the Gulf of Mexico (Rabalais et al., 1996; ibid 2001) and loadings of nitrogen (N) and phosphorous (P) from the Mississippi River system (Burkart & James, 1999; Goolsby et al., 2001). Similar concerns have been raised for Lake Erie (Bertram, 1993), and the Chesapeake Bay estuary (Officer et al, 1984; Correll, 1987; Jordon et al., 1997c). The importance of land use to water quality in general, and more specifically, the contributions of agriculture to nutrients loads has been documented by a number of recent studies (Johnson et al., 1997; Jones et al., 2000; Castillo, et al., 2000; Schilling & Libra, 2000).

In a pioneering study, Omernik et al, (1981) presented evidence of a correlation between the fraction of land in agricultural usage and the N and P concentrations in a series of small watersheds. Recent studies have verified the relationships between N-loadings and land usage (Howarth et al., 1996; Burkart & James, 1999, and Goolsby et al., 1999). The P-loads however more often correlate with geologic aspects (e.g., sedimentary deposits) of the surrounding land mass rather than human land use (Jordan et al., 1997a,b; Castillo et al., 2000).

We have examined the inter-relationships between land cover and the underlying topographical and geophysical surroundings as they impact nutrient concentrations (both N and P) in a set of 35 headwater streams distributed across 3 Omernik ecoregions of the Little Miami River watershed.

Little Miami River Watershed in Ohio
Omernik Level IV Ecoregions Shown

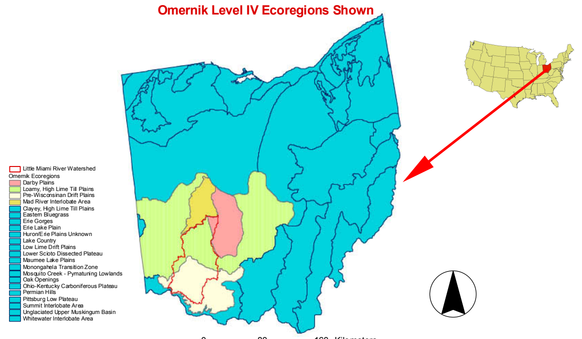

Figure 1.

Study Area. The Little Miami River (LMR) is a north-south orientated tributary of the Ohio River, draining a 5200 km2 catchment in southwestern Ohio and is described by an 8-digit Hydrologic Unit Code (Figure 1). The LMR drainage lies within the Eastern Corn Belt, a Level III Ecoregion with almost all (>97%) of that area contained in three of the smaller, Level IV ecoregion subdivisions, including, from north to south, the Darby Plain, the Loamy, High Lime Till Plain (Till Plain), and the Pre-Wisconsinan Drift Plain (Drift Plain). The Darby and Till Plains, which were graded by the Wisconsinan glacier, exhibit less topographic relief and much younger and less erodibile soils relative to the Drift Plains (Figure 2). In spite of these geologic differences the predominant land use category, throughout the entire LMR catchment, is row crop agriculture (Figure 3), including corn (*Zea mays*), soy bean (*Glycine max*), wheat (*Triticum aestivum*), and to a lesser extent some feed grains e.g., oats (*Avena sativa*), vegetables and trees. Grassy cover including pastures and hay fields, as well as parks, golf courses and lawns is the second most extensive land cover across the LMR watershed. At present the percentage of land in the LMR that is devoted to housing and other impervious surfaces classes is relatively small however the western edge of the watershed contains the rapidly expanding metropolitan areas of Dayton (north) and Cincinnati (south), Ohio.

LMRW: Topography and Soil Permeability

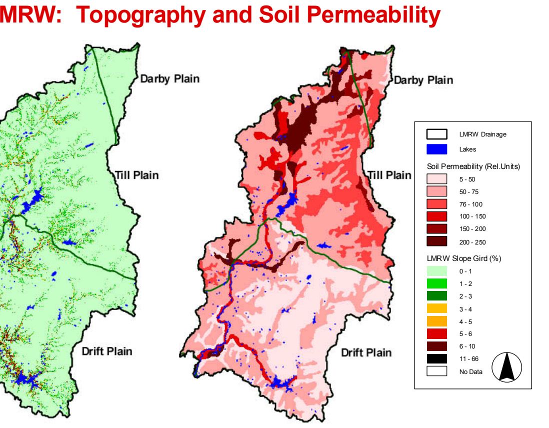

Figure 2.

Methods: The analysis of spatial data was conducted using the ArcView Geographic Information System (ESRI, Redlands, CA). All spatial data was converted an Albers Conical Equal Area projection for viewing and analysis. The study was conducted on a set of 35 headwaters streams (Figure 4) within the LMR watershed and initially selected from the USEPA RF3- stream reach file and are hereafter referred to as the LMR sub-watersheds. The drainage area of these sub-watersheds was calculated using a hydrologic model operating in the GIS software. Pour points were adjusted so that the sub-watershed catchment areas derived from the model ranged between 30 - 50 km2. The land cover in these catchment areas was determined by using ArcView GIS with the spatial analyst extension via overlay on the National Land Cover Dataset (NLCD) grid, created by classification of LandSat Thematic Mapper satellite imagery from the early 1990's (Vogelmann et a., 1998). The mean grade of the land with in the study sub-watersheds was calculated in the ArcView GIS using the National Elevation Data Set based on 30-meter resolution. Similarly, weighted mean soil characteristics for the individual sub-watersheds were determined from the STATSGO data for Ohio by aggregating the various soil parameters for soil layers of those soil map units that are within the LMR watershed boundaries using the aggregation procedures outlined by Shirazi et al., 2001, and were converted to a grid coverage using ArcView GIS spatial analyst.

LMRW: Land Cover
National Land Cover Dataset

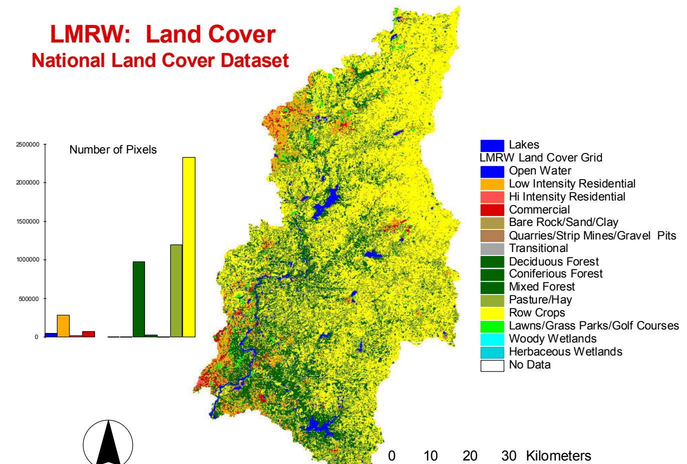

Figure 3.

Nutrient Chemistry: Water samples for nutrient chemistry were collected in March 2000 and March 2001 by grab samplings from mid-stream at mid-channel so as not to disturb steam bed sediments and placed on ice for transport to the laboratory. Samples were filtered through a 0.45 μ glass fiber frit within 12 hours of collection and stored in the dark at 4°C until analysis. The filtered samples were analyzed for a panel of dissolved nutrient parameters including total phosphorus (TP), total Kjeldahl nitrogen (TKN), nitrate plus nitrite nitrogen (NN), dissolved ammonia nitrogen (AMN), and chloride (Cl) and sulfate (SO4) using EPA standard methods (Standard Methods, 1998). The quality assurance and control process included:1) subtraction of field blank values from all of the sample unknowns to control for possible sample contamination and other sources of uncertainty and 2) use of split-sample duplicate variance as an estimate of method precision.

Statistical Analysis: The relationship between spatial features (e.g., land cover and geological) and water chemistry was evaluated using Systat-10 software (SPSS, Chicago, IL). An analysis of variance ANOVA with Boniferroni estimate of probabilities was used to confirm differences between the various ecoregions as regards the quantity of the various individual land cover or other spatial elements features (e.g., percent forest). Pearson's correlation coefficients were used to examine the strength and significance in the relationship between land cover and geologic features and water chemistry concentrations. Those spatial features showing significant (P</= 0.05) correlations either positive or negative, with water nutrient concentrations used as independent variables in a step-wise multi-regression model to relate spatial features with nutrient concentrations in the study streams.

LMRW Study Sub-watersheds

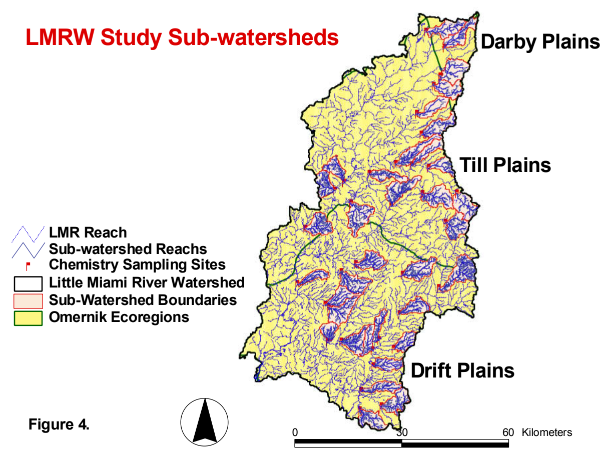

Figure 4.

Results & Discussion: Spatial analysis in the GIS shows that 16 of the sub-watersheds lie entirely (or predominantly) within the Drift Plain, 15 are in the Till Plains and 4 are within the Darby Plain area (Figure 4). The area, perimeter, length of stream reach, drainage density, and weighted mean surface gradient of the 35 sub-watershed catchments are well matched and do not differ significantly when compared across the three ecoregions (Table 1).

In contrast, a comparison of a series of mean-weighted soil characteristics for the catchment areas of the 35 sub-watersheds reveals significant differences across the ecoregions (Table 2). The soils in the Drift Plain present significantly greater mean-weighted surface erodibility and higher mean weighted percent clay content, leading to lower permeabilities and greater bulk densities than those in the Till and Darby Plains.

While all of the LMR sub-watersheds are set in predominantly agricultural landscapes, there are significant differences (ANOVA) in the relative percentages of the land cover classes in sub-watersheds within the three ecoregions. The Drift Plain watersheds contain, on average, significantly less area in row crop agriculture and more area in forest and grass cover than those in the Till and Darby Plain ecoregions (Table 3). Across the entire LMR, the land area devoted to row crop cover is inversely related to those occupied by forest and/or grass cover. The dominant trend is an increasing percentage of row crop, and concomitant decreasing percentages of grassy and forest cover, along the southwest to northeast diagonal (i.e., Drift Plain to Till Plain to Darby Plain) in the LMR watershed.

The levels of dissolved in-stream nutrients also showed consistent, significant differences across the 3 ecoregions with the streams in the Till and Darby Plains consistently containing significantly higher (27 – 42-fold) concentrations of NN, and significantly lower concentrations of ON and TP than those streams in the Darby Plain ecoregion (Table 4). The spatial distributions of dissolved nutrients are shown in Figures 6 & 7. The all of the sub-watersheds with the highest concentrations of NN are in the Till and Darby Plains (Figure 6). The NN/ON concentration ratios were typically, less than 4 in the Drift Plain sub-watersheds, while ranging from 28 – 73 in the Darby Plain (Figure 7)

Table 1. Geophysical Factors for LMRW Sub-Watersheds

	Drift Plain		Till Plain		Darby Plain	
Physical Parameter	Mean	SD	Mean	SD	Mean	SD
Catchment Area	26.2	6.6	31.6	8	32.4	4
Catchment Perimeter	35.4	5.3	41.2	6.2	43.2	5.2
Reach Length	66.2	19.7	74.4	40	48.9	5.1
Drainage Denisty	2.5	2.5	2.3	0.8	1.5	0.2
Mean-Weighted Slope	1.3	0.5	1.1	0.1	1.0	0.1

Text color indicates significant difference; p<0.05; ANOVA.

Table 2. Mean-Weighted Soil Factors for Sub-Watersheds

	Drift Plain		Till Plain		Darby Plain	
Soil Parameter	Mean	SD	Mean	SD	Mean	SD
Erodibility (K-factor)	0.423	0.004	0.361	0.013	0.349	0.012
Permeability (in/hr)	0.193	0.098	0.676	0.159	0.793	0.132
Clay (%)	34.73	0.21	30.52	2.39	27.41	0.37
Bulk Denisty (g/cc)	1.88	0.017	1.86	0.09	1.71	0.09
Organic Matter (wgt.%)	0.479	0.017	0.560	0.234	0.383	0.255

Text color indicates significant difference; p<0.05; ANOVA.

Table 3 Percent Land Cover By Class for LMR Catchments

	Drift Plain		Till Plain		Darby Plain	
Cover Class	Mean	SD	Mean	SD	Mean	SD
Row Crop	44.8	12.7	68.9	17.6	87.2	3.7
Forest	21.1	9.2	8.3	6.7	3.3	1.6
Grass	32.3	6.9	21.4	10.5	9.2	1.9
Impervious	1.5	1.3	1.2	1.5	0.2	0.3
Wetland	0.1	0.1	0.2	0.5	0.1	0.1
Water	0.1	0.1	0.2	0.2	0.04	0.04

Text color indicates significant difference; p<0.05; ANOVA.

Table 4 Mean Chemical Concentrations For LMR Catchments By Ecoregion

	Drift Plain		Till Plain		Darby Plain	
Analyte	Mean	SD	Mean	SD	Mean	SD
TP	0.06	0.02	0.04	0.02	0.03	0.02
NN	0.27	0.47	7.24	3.77	11.21	3.09
KN	0.45	0.25	0.35	0.14	0.36	0.16
AM	0.02	0.03	0.03	0.04	0.04	0.05
ON	0.42	0.23	0.32	0.13	0.32	0.14
CL	37.69	12.45	43.36	13.93	28.89	7.74
SO	56.69	19.46	46.05	17.80	72.01	27.93
TAN	94.38	24.25	89.41	22.29	100.89	28.39

Change in text color indicates significant difference; p<0.05; ANOVA.

LMRW: Row Crop Land Cover

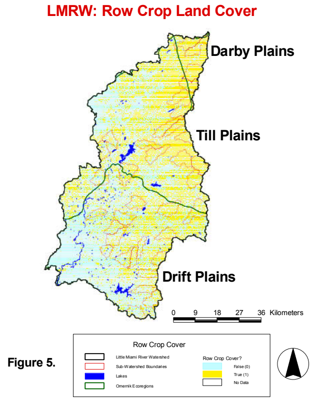

Figure 5.

LMRW: Dissolved Nitrate Concentrations
Spatial Distribution across Ecoregions

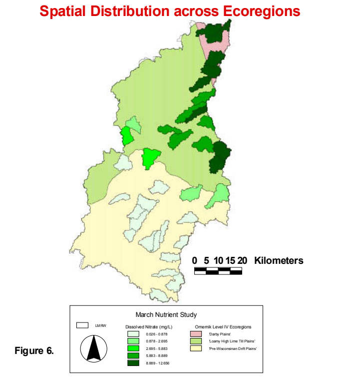

Figure 6.

LMRW: Nutrient Concentration Distributions

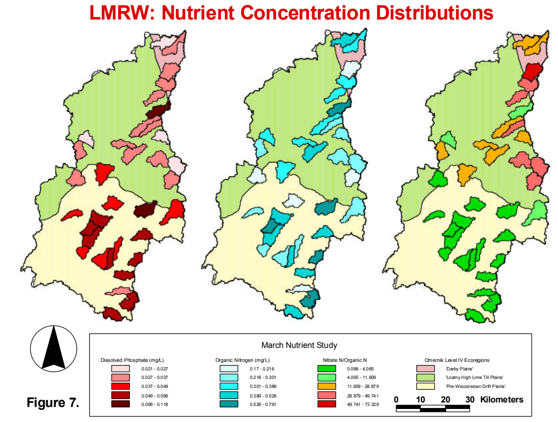

Figure 7.

The concentration of NN showed a significant correlations with two classes of landscape parameters measured in this study: land cover (Table 5), and soil characteristics (Table 6). The concentration of TP exhibited correlations with some of the soil parameters but not with the land cover features. In contrast, the concentrations of other analytes including ON, KN, AM CL, SO and TAN (total anions) did not show a correlation with either soil characteristics or land cover features (Tables 5 & 6). Specifically, the concentrations of NN correlate with the percentages of the catchment that is devoted to row crop agriculture and are inversely correlated with the percentages of forest or grass cover (Table 6). A plot of the relationship between the dissolved NN concentration and the percentage of catchment devoted to row crop agriculture for the LMR study sites is depicted in Figure 8. Figure 9 shows a similar a plot of the concentration of NN versus a soil characteristic, the mean-weighted soil permeability.

The strength of the land cover versus NN correlation, r2 = 0.73 is similar to that seen in earlier studies (cf. references). However, the relationships between either row crop cover or soil permeability and dissolved NN concentration does not appear to be a simple linear one (Figure 8 & 9). For example, Figure 10 shows a that the slope of the percent row crop cover versus NN is markedly different for the three ecoregions. The slope for the Till Plain sub-watersheds (~ 0. 2) is approximately 10-fold that of the Drift Plain sub-watersheds (~ 0.02). The slope for the Darby Plain sub-watersheds appears to be greater than then that for the Till Plain sub-watersheds. Soil characteristics are also differentially distributed across the Omernik ecoregion. This can be seen in the plot of the mean-weighted surface erodibility versus mean-weighted soil permeability is shown in Figure 11.

Table 5. Land Cover vs. Water Chemistry (Pearson Coefficients)

Analyte (mg/L)	% Row Crop	% Forest	% Grass	% Imperv. Surface	% Wet-land	% Open Water
TP	-0.226	0.136	0.27	0.17	0.256	-0.152
NN	0.853	-0.757	-0.817	-0.422	0.012	-0.158
KN	-0.051	-0.037	0.118	0.095	0.181	-0.203
AM	0.289	-0.316	-0.228	-0.071	0.254	-0.24
ON	-0.104	0.016	0.165	0.113	0.147	-0.172
CL	-0.037	-0.052	0.068	0.369	0.304	0.091
SO	-0.022	-0.006	0.05	-0.03	0.011	-0.026
TAN	-0.04	-0.034	0.082	0.182	0.181	0.028
		p<0.05;	p<0.01;	p<0.001		

Table 6. Soil Characteristics vs. Water chemistry (Pearson Coefficients)

Analyte (mg/L)	Surface Erodibility K-factor	Permi-ability (in/hr)	% Clay Content	% Organic Matter	Bulk Density (g/cc)
TP	0.508	-0.504	0.408	-0.127	0.137
NN	-0.867	0.855	-0.892	-0.039	-0.61
KN	0.264	-0.288	0.153	0.046	0.017
AM	-0.182	0.164	-0.233	-0.028	-0.191
ON	0.311	-0.332	0.203	0.053	0.051
CL	-0.029	0.025	-0.004	0.196	0.091
SO	0.161	-0.12	0.023	-0.143	-0.178
TAN	0.126	-0.092	0.018	-0.016	-0.106
	p<0.05;	p<0.01;	p<0.001		

Concentration Nitrate v. Percent Row Crop Cover

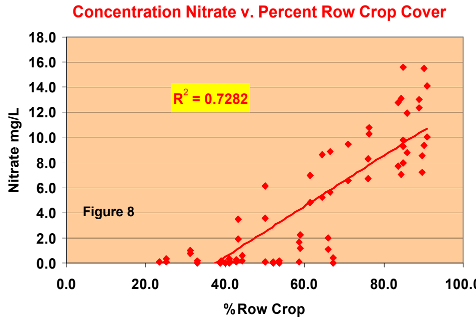

Figure 8

Concentration Nitrate v. Soil Permeability

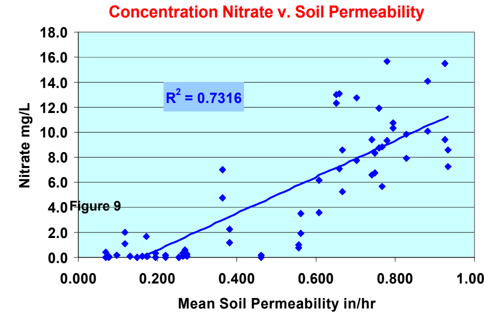

Figure 9

Nitrate Concentration v. Percent Row Crop By Ecoregion

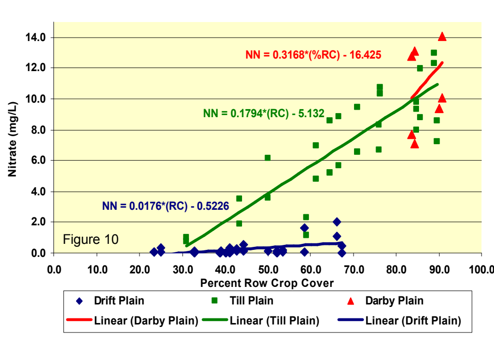

Figure 10

Soil: Errodibility v. Permeability by Ecoregion

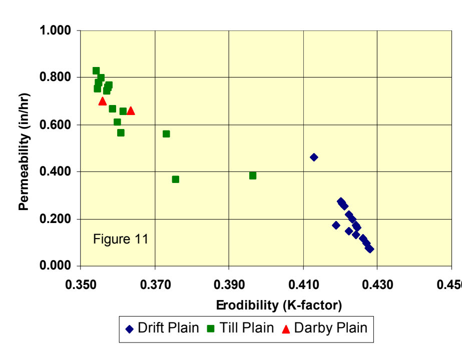

Figure 11

These observations were consistent with the hypothesis that across these three Omernik ecoregions, land cover and the other landscape factors, (e.g., soil characteristics, or geophysical factors) may also be acting in concert, in an additive or even synergistic manner, to influence in-stream nutrient concentrations. To examine this hypothesis we employed a step-wise, multi-regression technique to in order to determine which spatial features were influencing the concentration of dissolved nutrients. The independent variables for these models were those physical (e.g., watershed area), land cover (e.g., forest cover), and soil characteristics (e.g., erodibility), which showed a significant correlation (p< 0.05) with the analyte in question (Table 8).

This approach was successful for NN wherein 90 % of the measured stream concentrations could be explained in terms of three variables: percent row cropland cover, drainage density (i.e., km of stream reach per unit catchment area); and mean-weighted surface soil erodibility of the catchments (Table 9). Thus this model would indicate that, in the LMR, land cover features in acting concert with soil and geophysical measures to influence NN concentrations. However this modeling approach was considerably less successful for explaining the concentrations of TP, ON or any of the other analytes (Table 9). In the case of the other key nutrients, TP and ON, less than 50% of the in-stream concentration variance could be explained in terms of the independent variables used in this analysis. Inspection of Tables 5 and 6 reveals that this result might be expected as the in-steam concentration of these two analytes showed only marginal correlation with the various land cover and soil parameters. Previous, studies attempting to relate landscape features to in-stream nutrient concentrations have observed that TP correlates with geologic features. A limitation of this study lies in the fact that these samples were filtered prior to analysis resulting in information on dissolved total phosphate rather than true total phosphate concentrations. While neither TP or ON show a significant correlation with the landscape features employed in this study they do show a significant correlation with each other (0.791, p<0.001). In addition, in contrast to the situation observed with NN, the average concentrations of both of these analytes are higher in the Drift Plain sub-watersheds compared to those of the Till and Darby Plains (Table 4).

Table 8. Independent Lanscape Variables for Stepwise Multi-Rregression Models

Geophysical Measures		Designation		Units
Catchment Area		AR_KM2		km^2
Catchmen Perimeter		PR_KM		km
Kilolmeters of Stream (Reach)		RF4_KM		km
Drainage Density		D_DEN4		km^{-1}
Mean-Weighted Surface Slope		SO_KW		%
Soil Measures				
Mean-Weighted Surface Layer Soil Erodibility		SO_Kw		K-factor Units
Mean-Weighted Soil Permeability		PERMW		in/hr
Mean-Weighted Soil Percent Clay		P_CLAYW		%
Mean-Weighted Soil Percent Organic Matter		P_ORMW		%
Mean-Weighted Soil Bulk Density		B_DENW		gm/cc
Land Cover Measures				
Percent Row Crop Agriculture Cover		P_ROCRP		%
Percent Forested Cover		P_FORST		%
Percent Grassy Cover		P_GRAS		%
Percent Impervious Surface		P_IMPRV		%
Percnet Wetland Cover		P_WETL		%
Percent Open Water Cover		P_WATR		%
Other Measures				
Kilometers of Roadway		ROAD_K		km
Number of Bridges		N_BRDG		units

Table 9. Step-Wise Multi-Regression Models For Stream Analytes

Analyte	Independent Variables Retained	Multiple R^2
Nitrate Nitrogen (NN)	D_DEN, SO_Kw, P_ROCRP	0.90
Total Phosphate (TP)	SO_Kw, P_FORST. P_WETLD	0.49
Organic Nitrogen (ON)	PERMW, P_CLAYW, P_ORMW, P_FORST, P_WETLND	0.31
Ammonia Nitrogen (AM)	P_FORST, P_WETLND	0.16
Kjeldahl Nitrogen (NN)	PERMW, P_CLAYW, P_ORMW P_FORST, P_WETLND	0.31
Chlorides (CL)	P_CLAYW, P_ORMW, P_FORST P_IMPRV, P_GRAS. N_BRIDG	0.48
Sulfates (SO)	D_DEN, SO_Kw	0.10

Conclusions: 1) The most significant finding of this study is the apparent influence landscape features within the Level IV Omernik ecoregions on the patterns of the dissolved in these sub-watersheds. The most striking observation is the marked variation in the concentration of dissolved NN across the ecoregions. The average concentrations of NN observed in the Darby and Till Plain sub-watersheds were up to 100 times those seen in contemporaneously sampled the Drift Plain sites. Even when comparing sub-watersheds of with comparable percentages of the catchment surface devoted to row crop agriculture, the concentrations of dissolved NN average 5 – 10 fold higher in the Till and Darby Plains relative to those in the Drift Plain (data not shown).

2) The observed differences in NN concentrations are more likely attributed to the differences in soil characteristics between the ecoregions rather than difference in the topography. The mean-weighted slope values measured for all the sub-watersheds are similar and very modest (1 – 1.3%, cf Table 3) and are much less than the 3 –4 % grades typically associated agriculturally induced soil erosion (Wischmeier & Smith, 1978). In contrast, there are significant differences in the soil characteristics between the three ecoregions (Table 2). The soils resulting from the impacts of the Wisconsinan glacier, in the Darby and Till Plains, are typically of a lower bulk density and clay content, are more permeable, and are less prone to erosion then those produced by the earlier glacial events in the Drift Plain. Further, these differences in soil characteristics exhibit significant correlations with the dissolved nutrient concentrations (Table 6).

3) Although, ecoregional differences in other nutrient concentratios were observed (e.g., TP and ON), the use of stepwise multi-regression to construct models relating landscape features to in-stream analyte concentrations were only sucesssful for NN . These studies will be expanded to include effects of spatial scale, e.g., riparian land cover on nutrient concentrations and to convert nutrient concentrations to loadings via the construction of flow models for the LMR sub-watersheds.

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